A METHOD TO ESTIMATE INJURY MEDICAL COST OF OCCUPANTS IN A CRASH TEST

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ABSTRACT

In a laboratory crash test, the injuries of occupants, such as Head Injure Criterion (HIC), N_{ij}, Combined Thorax Index (CTI) etc., can be obtained and transferred to the Abbreviated Injury Scale (AIS). The calculated AIS value usually represents the severity of injury and can be adopted to evaluate the safety of the test vehicle. However, the AIS cannot reflect the medical resources consumed due to various vehicles of different designs. This study presents a statistical method to estimate injury medical cost from the AIS value of an occupant in a crash test. A frontal impact case study is illustrated. Five steps are carried out as follows:

1. To link the following three Taiwan's databases by the individual identification number: crash data reported by police officers, hospital data recorded in the health insurance database, and death database.
2. To calculate AIS values by the diagnosis ICD-9-CM code written by doctors for each individual case.
3. To develop a statistical model to estimate medical cost from massive crash cases obtained in steps 2.
4. To simulate crash test for obtaining the injuries of occupant by using a validated finite element simulation model of Hybrid III 50th percentile male dummy. The injuries of occupant are then converted to AIS values.
5. To estimate the probable medical cost by the statistical model using the predicted AIS values from the crash test simulation.

INTRODUCTION

Crash test required in the standards like FMVSS 208 is expected to get the minimum safety protection of the test vehicle. In addition to evaluate the basic required safety criteria, a computer simulation test can further predict the occupants' injury of slight changes in vehicle design and restrained features. On the other hand, the qualified vehicle models being driven on the road by different drivers in the real world would be involved in the crashes unavoidably. Then, data linkage technique could be used to link different real crash databases to explore more information between the real world and the crash test. In order to use the engineering variables of the dummy in the crash test to evaluate the injury type and severity of the occupants, the injury criteria such as Head Injure Criterion (HIC), N_{ij}, Combined Thorax Index (CTI) etc., can be obtained and transferred to the Abbreviated Injury Scale (AIS). The calculated AIS value usually represents the severity of injury. It can be obtained through biomechanical test-based injury risk functions (Kleinberger et al., 1998; Kuppa et al., 2001; Kuppa, 2004; Kuchar, 2001; Newman et al., 1994).

The biomechanical cost model proposed by Newman et al. (1994) utilized injury risk functions to predict the occurrence probability of different AIS scores to the head, thorax, and abdomen (Newman et al., 1994). For a particular body region, average medical and ancillary cost of a specific AIS score multiplied by its probability was used to forecast the probable cost of an injury.

Kleinberger et al. (1998) conducted an examination of biomechanical results and real world data in the frontal crash, and adjusted a set of logistic regression models of injury risk for the Hybrid III 50th percentile male dummy. The injury criteria used in their study were HIC36 (Head Injury Criteria) to head, N_{ij} to neck, CTI (Combined Thoracic Index) to chest, and Femur load to lower extremity. Also, Kleinberger et al. proposed risk functions AIS $\geq$ 3 of neck N_{ij} and AIS $\geq$ 5 of chest CTI. The risk function of head HIC36 AIS $\geq$ 2 developed by Hertz in 1993 was presented in Kleinberger's study (1998).

A more complete Hertz's HIC36 risk functions including AIS ≥ 2, AIS ≥ 3, and AIS ≥ 4 were shown in the study of Kuppa (2004). Kuppa et al. (2001) used existing biomechanical data on lower extremity injuries and regression method to synthesize injury criteria and associated injury risk functions of AIS ≥ 2. Kuchar (2001) also used HIC36 and CTI risk functions proposed by Kleinberger et al. (1998) in his systems modeling approach to assess harm in the crash environment.

The injury risk assessment of mechanical surrogate of human cannot predict the medical cost of the injury. But, the medical burden is a major concern of injury prevention in the real world. Rosman and Hendrie (2002) presented a process by using Injury Cost Database, and linked hospital admission and death records of Western Australia to study the real world characteristics. ICDMAP software developed by John Hopkins University was used to convert diagnosis codes to AIS score for different body regions. Then a linear regression model of total medical costs was built up. Hendrie et al. (2001) developed a generalized linear model (GLM) to estimate crash medical costs of the body regions and AIS injury scores by using Road Injury Cost Database of New South Wales, Australia. The results indicated that GLM model could explain 36% of the variation in the total cost of injuries in the Road Injury Cost Database. Lawrence et al. (2002) noted a significant low medical cost of the fatality showing a necessary to discuss them separately from the survivals. The fatality and the survivals had different probability cost models in the Newman's study (Newman et al., 1994) too.

Owing to the gap between injury assessment of biomechanical test and the medical burden concern in the real world, the AIS concept could be applied as a bridge to the gap. In the present study, real crash, hospital and death records of Taiwan are linked to develop a medical cost model of various crash injury severities. A validated finite element simulation model of Hybrid III 50th percentile male dummy is used to simulate injury in the crash test. Then the computer simulation outputs are substituted to the medical cost model to calculate the probable medical cost of the predicted injury.

METHODS

Medical Cost Model

Using real world data of Taiwan can develop a medical cost model. A lot of useful information in crash database, health insurance database, and death database can be found by data linkage technique. Table 1 shows the data items used in the present study. The three databases all includ an individual identification number (ID) to indicate whose data was recorded. The ID is a specified number issued by Taiwan's government when a baby was born. Therefore, it is possible to obtain associated data of a particular person by using data linkage technique via ID in crash, health insurance, and death databases. In the present study, crash and death records are linked via ID firstly, to separate survivals from the fatality. Then the IDs of the survivals are linked to health insurance database, to obtain their hospital treatments records and costs.

Table 1.
The data items used in the present study

Database	Data items
Crash	individual identification number (ID) victim type (driver, passenger etc.) crash type (frontal crash, side crash etc.) vehicle type (passenger car, bus etc.) crash occurrence date
Health insurance (hospital data)	individual identification number (ID) 3~5 ICD-9-CM codes treatment type (hospitalized, outpatient services, emergency treatment etc.) medical expenditure admission date
Death	individual identification number (ID) death date

Software ICDMAP 90 developed by the John Hopkins University and Tri-Analytics, Inc. can convert ICD coding system in the large pre-existing medical database to AIS coding system. The principle ICD-9-CM diagnosis code in each of Taiwan's injury hospital records is converted to the AIS score (1 to 6, 6 is for dead subject) and body region (1 to 10). Then, a new database can be generated, including victim type, crash type, vehicle type, medical expenditure, AIS score, and AIS body region data of each person involved in the crash.

Different crash types can result different probabilities of body regions injury. While a specific region injured, any severity is possible, and various degree of injury will have significant influence on the variety of medical cost. According to this causation, the equation of medical cost model is as follows:

$$C = \sum_{j=1}^{n} \sum_{i=1}^{5} S_j P_{ij} C_{ij} \qquad (1).$$

where

i : is the level of injury, defined by AIS scores (1 to 5)

j : is a particular AIS body region injured (1 to 10).

S_j : is the probability of each body region j injured in a specific crash type, such as frontal crash.

P_{ij} : is the probability of a particular AIS score i to a specific body region j.

C_{ij} : is the medical cost of each body region j injured with AIS score i.

Logistic regression is used to develop the probability equations of S_j from real crash data in Taiwan. A mathematical relationship between the dichotomous dependent variable ('injury' and 'no injury') and independent variable (crash type) is estimated. Wald statistics Z^2 (coefficient β dividing its approximating standard error) and -2log-Likelihood Ration are used to examine the significant of the coefficient and the goodness of fit of this logistic regression model respectively. Linear and non-linear regressions are used to calculate C_{ij} from Taiwan's real crash data. The AIS score is the independent variable, and medical cost is the continuous dependent variable. R^2 is used to examine the explanation ability of fitted C_{ij} equations. The P_{ij} are calculated directly from the injury risk functions proposed by Kleinberger et al. (1998), Kuppa (2004), and Kuppa et al. (2001).

Finite Element Simulation

Software LS-DYNA3D is used to simulate the dynamic responses of Hybrid III 50th percentile male dummy (regulations of FMVSS 49CFR PART 572E) restrained with a seatbelt (regulation of FMVSS 208) in a frontal impact sled test. The simulation model is validated according to Prasad's (1990) experiment results. In the present study, the test speed is 30mph (FMVSS 208 requirement). The impact on the head, neck, thorax, and knee of the simulation dummy is compared to the result of Khali's (1994) study. Injury criteria based on FMVSS 208 (HIC36 to head and Nij to neck), NHTSA suggestion (CTI to thorax), and Kuppa et al. (2001) result (force to femur) are calculated from simulation outputs.

Crash Injury Medical Cost Prediction

The injury criteria calculated in the above section are converted to the probabilities of various AIS scores by using the equations (2)~(5) which are the injury risk functions of mid-sized adult male based on biomechanical tests from the other studies. Except the seatbelt and the seat, there is no other interior equipment in the sled simulation model. Therefore, the femur and the thorax of the simulated dummy cannot response reasonably in the simulation model. The associated injury criteria of femur and thorax are not calculated. In the future, this shortage can be overcome when the simulation model is upgraded from sled model to full vehicle model.

Head: (Kuppa, 2004)

$$P(AIS \geq 3) = \phi\left(\frac{\ln(HIC_{36}) - \mu}{\sigma}\right)$$
$$\mu = 7.45231, \sigma = 0.73998 \qquad (2).$$
$$\phi: \text{accumulative normal distribution}$$

Neck: (Kleinberger et al., 1998)

$$p(AIS \geq 3) = \frac{1}{1 + e^{3.906 - 2.185 N_{ij}}} \qquad (3).$$

Thorax: (Kleinberger et al., 1998)

$$p(AIS \geq 3) = \frac{1}{1 + e^{7.529 - 6.431 CTI}} \qquad (4).$$
$$CTI = \frac{A_{max}}{A_{int}} + \frac{D_{max}}{D_{int}}$$

Femur: (Kuppa et al., 2001)

$$p(AIS \geq 3) = \frac{1}{1 + e^{4.9795 - 0.326 F}} \qquad (5).$$

The outputs of equations (2)~(3) are substituted into the P_{ij} in the equation (1), together with the associated S_j and C_{ij} stated in the above, to estimate the probable medical cost resulted from passenger car driver in the frontal impact.

RESULTS

Real Crash Data Analysis

There are 330 thousands crash victims reported by police in Taiwan from year 1999 to 2001. 7087 of them are found in the death records, 1118714 survived victims are successfully linked to hospital data. Among 1118714 survivals, 15177 are passenger car drivers. 7 of these 15177 drivers are assigned AIS = 6 by ICDMAP 90, 7182 drivers are in unknown injury state, and 7988 drivers are survived in AIS 1~ 5. Among 7988 survival drivers, 1737 drivers (21.7%) are involved in the frontal crashes. It can be seen in Table 1 that 871 (50.1%) of these 1737 drivers are head injured, 242 drivers (13.9%) are thorax injured, and 290 drivers (16.7%) are lower extremity injured. Very few neck injured survivals are recorded in Taiwan's data and there are not enough to build up the C_{ij} equation of the neck. Among the survived drivers in the frontal crash, most of them are AIS < 4 injuries.

Table 1.
Number of survived passenger car driver by principle injured body region and AIS score in frontal crash

	AIS score					Total	
body region	1	2	3	4	5	counts	%
Head and face	512	273	31	48	7	871	50.1
Neck	1	0	1	0	0	2	0.1
Thorax	207	16	19	0	0	242	13.9
Lower extremity	95	129	65	1	0	290	16.7
Others	208	102	14	7	1	332	19.2
Total	1023	520	130	56	8	1737	100.0

The original medical cost distribution and transformed natural logarithm function data are a marked positive skewness (See Figure 1) and an approximating normal distribution (See Figure 2), respectively. This attribute of medical cost distribution is same trend in each body region. Therefore, natural logarithm of medical cost is used during the regression.

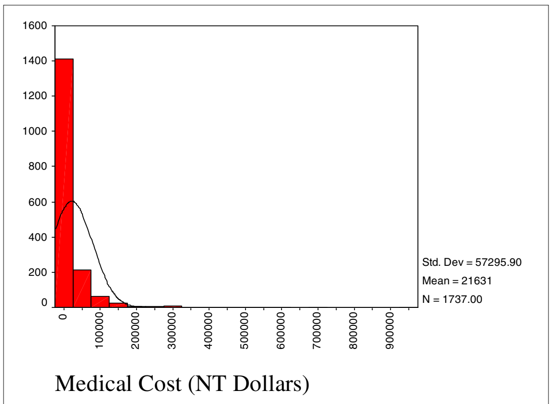

Figure 1. Original medical cost distribution of survived passenger car driver in frontal crash. (1 US dollar = 33 NT dollar)

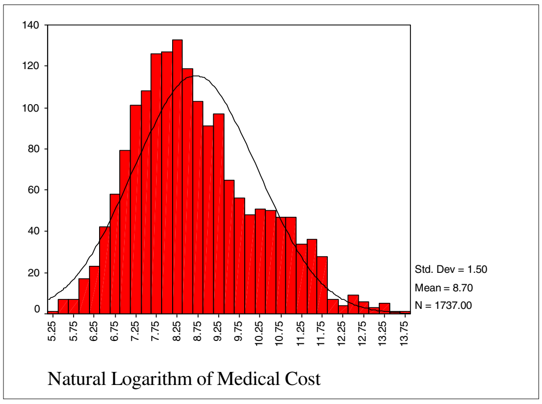

Figure 2. Natural logarithm of medical cost distribution of survived passenger car driver in frontal crash.

S_j and C_{ij} Models Development

Equations (6)~(8) and (9)~(11) are the fitted regression functions for S_j and C_{ij}, respectively. From equations (6)~(8), the probability to head, thorax, and lower extremity injured in the frontal crash are in the sequence of 0.56, 0.1, and 0.1. The fitted regression functions (9)~(11) to head, thorax, and lower extremity could explain 20%, 30%, and 50% of the variation in the associated medical cost. All the coefficients in equations (6)~(11) are statistical significant. Owing to the few records number of neck injury, the associated equations cannot be obtained in the present study.

$$S_j = \frac{e^{\alpha+\beta x}}{1+e^{\alpha+\beta x}}$$

$$x = 1 \text{ for frontal crash}, 0 \text{ for other crashes}$$

j = Head and face

$$\alpha = 0.0058 \quad \beta = 0.2474 \tag{6.}$$

j = Neck, associated data were too few to fit equation.

j = Thorax

$$\alpha = -1.8209 \quad \beta = -0.3191 \tag{7.}$$

j = Lower extremity

$$\alpha = -1.6074 \quad \beta = -0.5689 \tag{8.}$$

i = AIS scores, and

j = Head and face

$$C_{ij} = e^{7.541+0.640AIS} \tag{9.}$$

j = Neck, associated data were too few to fit equation.

j = Thorax

$$C_{ij} = e^{6.718+1.129AIS} \tag{10.}$$

j = Lower extremity

$$C_{ij} = e^{4.156+4.497AIS-0.751AIS^2} \tag{11.}$$

Validation of the Finite Element Simulation Model

The validation of the finite element simulation model is done by comparing the simulation output in the present study to the test results of Prasad's (1990) study. The acceleration curve used by Prasad is illustrated in Figure 3, 112ms time history and peaking at 23.7G. The same conditions are substituted into the simulation model to drive the sled. The resulted acceleration outputs are shown in table 2. In general, there is acceptable agreement in these results between the present simulation model and Prasad's study.

Table 2.
Comparison between sled simulation and Prasad's (1990) sled test.

Acceleration		Simulation	Prasad (1990)
History	Head	Figure 4.	
	Thorax	Figure 5.	
	Pelvis	Figure 6.	
Peak	Head	62G	58G
	Thorax	47G	43.5G
	Pelvis	51.5G	55G

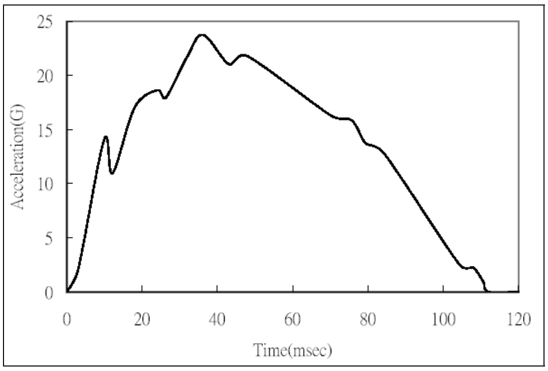

Figure 3. Frontal impact sled test pulse from Prasad (1990).

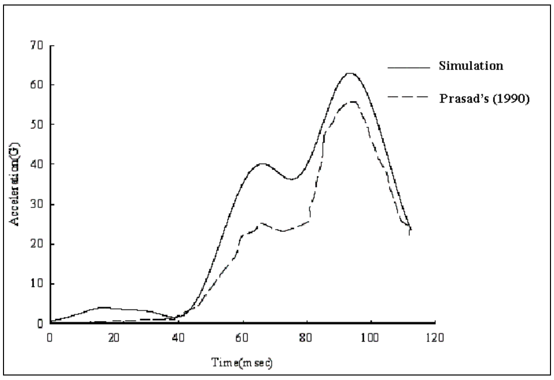

Figure 4. Head acceleration comparison between sled simulation and Prasad's (1990) sled test.

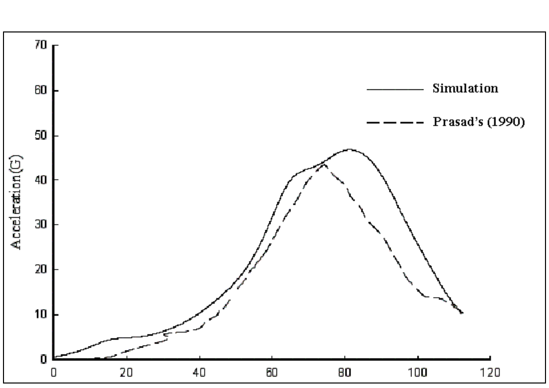

Figure 5. Thorax acceleration comparison between sled simulation and Prasad's (1990) sled test.

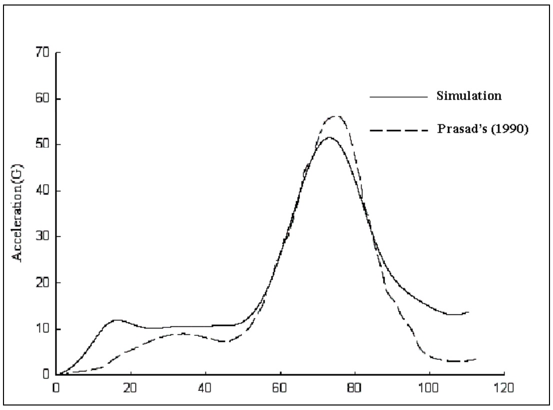

Figure 6. Pelvis acceleration comparison between sled simulation and Prasad's (1990) sled test.

Injury Criteria Calculation

By using validated finite element simulation model in the above section, a frontal crash test at 30mph (48kph) is simulated in the present study. Maximum acceleration during the frontal crash test simulation is 27.5G. Since only seatbelt and seat are included in the sled simulation model, the dynamic responses of thorax and femur cannot be simulated reasonably. The associated simulation results and the injury criteria are not stated here. It can be done when the simulation model is upgraded from sled to full vehicle model in the future. A value of HIC36=492.6 is calculated from the peak head acceleration 53.4G. The N_{ij} to neck injury are $N_{tension\text{-}flexion} = 0.85$, $N_{tension\text{-}extension} = 0.12$, $N_{compression\text{-}flexion} = 0.06$, and $N_{compression\text{-}extension} = 0.11$. $N_{tension\text{-}flexion}$ is the highest in these four N_{ij} . According to our simulation experience in N_{ij}, $N_{tension\text{-}flexion}$ also presented the most significant variation to test speed.

Probable Medical Cost Prediction

<u>Calculation the Probability of AIS Scores:</u> The probabilities of AIS ≥ 3 can be further calculated by substituting injury criteria, HIC36 and N_{ij}, into associated equations (2)~(3). Then, the probability of AIS < 3 can be obtained by 1 minus P(AIS $\geq$ 3). Because $N_{tension\text{-}flexion}$ is the highest and the most sensitive to test speed among the four N_{ij} values, it is used in the present study to represent the N_{ij}. Therefore, $N_{ij} = 0.85$ is substituted into equation (3). From the probability results shown as below, the frontal crash test at 30mph (48kph) would result AIS ≥ 3 to head and neck injury at a probability of 0.05 and 0.11, respectively.

Head:

$$P(AIS \geq 3) = \phi(\frac{ln(HIC_{36}) - \mu}{\sigma})$$
$$= \phi(\frac{ln(492.6) - 7.45231}{0.73998}) = 0.04525$$
$$\mu = 7.45231, \sigma = 0.73998$$
$$\phi : accumulative\ normal\ distribution$$
$$P(AIS < 3) = 1 - P(AIS \geq 3) = 0.95475$$

Neck:

$$p(AIS \geq 3) = \frac{1}{1 + e^{3.906 - 2.185 N_{ij}}}$$
$$= \frac{1}{1 + e^{3.906 - 2.185 \times 0.85}} = 0.11418$$
$$p(AIS < 3) = 1 - p(AIS \geq 3) = 0.88582$$

Probable Medical Cost Prediction: The probabilities of AIS $\geq$ 3 and AIS < 3 calculated in the above paragraph is used to represent the AIS = 1~5. The P(AIS $\geq$ 3) and P(AIS < 3) are the probabilities of AIS = 1~3 and AIS = 1~2, respectively. These probability values to head, associated with C_{ij} from equation (9) and S_j from equation (6), are substituted into equation (1) together to predict the medical cost of head injured to survival passenger car driver involved in the frontal impact. The predicted medical cost to head is NTD 7,687 per survival passenger car driver involved in the frontal crash. The calculation is demonstrated as below:

j = Head	P_{ij} (equation (2))		C_{ij} (equation (9))
i=AIS=1	0.95475	x	3572
i=AIS=2	0.95475	x	6775
i=AIS=3	0.04525	x	12849
i=AIS=4	0.04525	x	24367
i=AIS=5	0.04525	x	46212

$$\sum_{i=1}^{5} P_{ij} C_{ij} = 13654$$
$$predicted\ medical\ cost$$
$$= S_j \times \sum_{i=1}^{5} P_{ij} C_{ij} = \frac{e^{0.0058 + 2.2474 \times 1}}{1 + e^{0.0058 + 2.2474 \times 1}} \times 13654$$
$$= 0.56296 \times 13654 = 7687$$

Owing to the lack of enough neck injury records in the real crash data, the associated C_{ij} and S_j equations are not built in the present study. Therefore, the medical cost of neck, thorax and femur cannot be predicted. However, this can be done in the same way illustrated in the above when the sufficient associated data and a full vehicle model are available.

CONCLUSIONS

In the present study, several conclusions are as follows:

1. The head, thorax, and lower extremity medical cost model built in the present study can predict the probable medical cost of survivals in the frontal crash. It is possible to choose an economic index obtained from this model to evaluate car safety.

2. By data linkage technique, crash injury information in the real world can be continuously obtained and the statistic probability model can bridge the injury assessments between real world and laboratory test data.

3. Also, the improvement of injury protection due to car design and occupant restraint can cause the change of injury severity; therefore, the affect on the medical cost can be calculated.

4. In the future, more real crash data of neck injury and the full vehicle simulation model including femur and thorax output data can be used to overcome some shortages of present model.

5. In advance, the medical cost of the fatality and long term medical burden can be considered as the associated data are available.

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